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From Ethnobiology to Ecotoxicology: Fishers' Knowledge on Trophic Levels as Indicator of Bioaccumulation in Tropical Marine and Freshwater Fishes

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Abstract

Information on fish trophic levels is important to assess fishing impacts and to better understand the bioaccumulation of pollutants within aquatic food chains. The local ecological knowledge held by small-scale fishers can fill knowledge gaps in fish trophic ecology. We estimated the trophic levels of 69 tropical and subtropical fish species (33 coastal and 36 freshwater species) using data on fish diets from the literature and obtained from interviews with Brazilian fishers. The fish trophic levels estimated from fishers' knowledge were positively correlated with the trophic levels estimated using data from biological studies for both coastal and freshwater fish. The fishers' knowledge also indicated bioaccumulation patterns, as the fish trophic levels estimated from fishers' knowledge were positively related to the mercury (Hg) content in fish muscle (wet weight, from literature data) in 41 fish species (15 coastal and 26 freshwater). These findings reveal the potential for new applications of fishers' knowledge to ecotoxicology, which could improve management of aquatic ecosystems and strengthen fishers' political status.

Key words: aquatic contamination; pollution; mercury; fish diet; functional ecology; small-scale fisheries; fisheries management.

Introduction

Fish provide many ecological services in the form of food provisioning from fisheries or ecological processes mediated by fish feeding, such as bio-erosion, nutrient recycling, and seed dispersal (Bellwood and others 2003; Scheffer and others 2005; Mcintyre and others 2007; Anderson and others 2011). Knowledge about the trophic levels

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(TLs) of fish species can be useful to assess the potential ecological effects of fishing, including trophic cascades (Scheffer and others 2005) or simplification of food chains through a reduction in the abundance of species from high trophic levels (Pauly and others 1998; Estes and others 2011). Fish TLs also reflect the bioaccumulation patterns of toxins or pollutants, such as heavy metals, within aquatic food chains (Boischio and Henshel 2000; Bisi and others 2012). Because any ingested toxins or pollutants tend to become concentrated along the food chain, fish at higher TLs (predators) usually show higher concentrations of toxins or heavy metals, in both freshwater and coastal ecosystems (Bastos and others 2008; Bisi and others 2012). Therefore, fish TLs can be a useful indicator of the contamination of fish by heavy metals, such as mercury (Hg), and hence, of potential health risks to human consumers (Boischio and Henshel 2000). Despite the potential relevance to ecology, fisheries, and ecotoxicology, detailed data on fish feeding behavior and trophic position are still lacking for some species and regions, especially in tropical developing countries.

Small-scale local fishers have detailed knowledge about fish ecology, including fish feeding behavior (Silvano and others 2008; Silvano and Begossi 2010, 2012; Le Fur and others 2011; Ramires and others 2015). This local knowledge can inform fisheries and ecological research (Huntington 2011), especially in tropical developing countries where there is a deficit of scientific data (Johannes 1998; Johannes and others 2000; Begossi 2008). Local knowledge from fishers about fish migration, reproduction, critical habitats for use as nurseries or for spawning, and extinctions and temporal changes in abundance (Aswani and Hamilton 2004; Saenz-Arroyo and others 2005; Silvano and Begossi 2005; Silvano and others 2006; Lavides and others 2010; Hallwass and others 2013) has been useful for the formulation of new biological hypotheses (Silvano and Valbo-Jorgensen 2008) and informing fisheries management (Johannes and others 2000), thus helping to fill current knowledge gaps.

We compiled data on fishers' knowledge about the diets of 69 tropical and subtropical fish species (33 coastal and 36 freshwater species) from previous studies involving artisanal fishers in Brazil (Tables 1 and 2) and used these data to estimate the TLs of these fish. We aimed to compare the fish TLs determined from fishers' knowledge with (1) fish TLs according to the biological literature and (2) the mercury (Hg) contents (wet weight in fish muscle) of a subset of 41 fish species (15 coastal and 26 freshwater), for which these data were available in the literature (Tables 1 and 2).

Methods

Fishers' Knowledge

We gathered data (interviews) from previous studies conducted in artisanal fishing communities along the south, southeastern, and northeastern Brazilian coast and in the Negro and Tocantins Rivers in the Brazilian Amazon, including unpublished data (Table 1). This review was not a random or systematic search of the literature, and it mostly includes studies from our research group, in addition to other studies addressing threatened fish species, such as the mero (*Epinephelus itajara*) and seahorse (*Hippocampus reidi*) (Table 1). We chose these studies because they addressed fishers' knowledge about fish diets in detail, included many distinct fish species from various TLs, comprised relatively large sample sizes of interviewed fishers (usually 10 or more), and followed the same method to collect quantitative data. Similarly, the studied fish included only a small subset of the rich biodiversity of the Brazilian coast and the Amazon Basin, where there are thousands of fish species (Junk and others 2007). Nevertheless, the studied subset of fish species included a range of fish families with various ecological characteristics (Begossi and others 2008), representing most of the known trophic categories of fish (detritivores, herbivores, predators). Furthermore, some of the studied fish are among the most important commercial fish of marine and freshwater fish and are therefore better known by fishers and are the focus of concern regarding potential contamination by heavy metals and the effects of consumption by humans.

Along the northeastern Brazilian coast, the artisanal fishermen exploit lobster, shrimp, and fish from reefs, the open sea, and estuaries, generally using small boats and several types of fishing gear, including hook and line gear, gillnets, long lines, and lobster traps (Begossi and others 2011; 2012a). Along the southeastern Brazilian coast, artisanal fishers mostly use gill nets and hook and line gear to catch fish (mainly Pomatomidae, Serranidae, Mugilidae, Sciaenidae, Centropomidae, and Carangidae), shrimp, and squid (Begossi 2008; Begossi and others 2012b). Along the two studied Amazonian rivers (Negro and Tocantins), there are small-scale commercial fishers who use small boats and several types of fishing gear, such as gillnets, hook and line gear, and the zagaia (a small harpoon employed during the night to catch

Table 1. Data from Fish Species Analyzed in the Brazilian Coast

Fish species	Codes[1]	Region[2]	N fishers[3]	N fish Hg[4]	Species Hg	Sources
Abudefduf saxatilis	As	SE	49	None[5]	None	Begossi and others 2008, Silvano and Begossi 2012
Bodianus pulchellus	Bp	SE	21	None	None	Begossi and others 2008
Bodianus rufus	Br	SE	60	None	None	Begossi and others 2008, Silvano and Begossi 2012
Caranx crysos	Cc	SE/NE	46	3	*C. caninus*	Cai and others 2007, Begossi and others 2008
Caranx latus	Cl	SE	60	3	*C. caninus*	Cai and others 2007, Begossi and others 2008, Silvano and Begossi 2012
Centropomus parallelus	Cp	SE/NE	46	24	*Centropomus* spp.	Begossi and others 2008, Bisi and others 2012
Cephalopholis fulva	Cf	NE	42	25	Same	Lacerda and others 2007, Begossi and others 2012a
Cynoscion jamaicensis	Cj	SE/NE	46	18	Same	Begossi and others 2008, Silvano and Begossi 2012, Bisi and others 2012
Epinephelus itajara	Ei	S	7	None	None	Gerhardinger and others 2006
Epinephelus marginatus	Ema	S/SE/NE	266	1	Same	Begossi and Silvano 2008, Begossi and others 2008, Kütter and others 2009, Begossi and others 2012a, Silvano and Begossi 2012
Epinephelus morio	Emo	SE	21	None	None	Begossi and others 2008, Begossi and others 2012a
Epinephelus niveatus	En	S/SE/NE	61	None	None	Begossi and others 2012a
Eucinostomus argenteus	Ea	S	28	None	None	Nunes and others 2011
Euthynnus alleteratus	Eal	SE	21	None	None	Begossi and others 2008
Haemulon aurolineatum	Ha	SE	28	33	*H. steindachneri*	Rodrigues and others 2010, Silvano and Begossi 2012
Hemiramphus balao	Hb	SE	28	None	None	Silvano and Begossi 2012
Hippocampus reidi	Hr	NE	181	None	None	Rosa and others 2005
Kyphosus spp.	Ks	SE	39	None	None	Silvano and Begossi 2012
Lutjanus synagris	Ls	SE/NE	101	79	*Lutjanus* spp.	Bank and others 2007, Begossi and others 2008, Begossi and others 2011
Menticirrhus americanus	Ma	SE	21	33	Same	Begossi and others 2008, Nunes and others 2011, Bisi and others 2012
Micropogonias furnieri	Mf	SE	49	175	Same	Kehrig and others 2002, Begossi and others 2008, Kütter and others 2009, Rodrigues and others 2010, Nunes and others 2011, Bisi and others 2012, Silvano and Begossi 2012
Mugil curema	Mc	S/SE	45	30	*Mugil* spp.	Kehrig and others 2002, Begossi and others 2008, Nunes and others 2011, Bisi and others 2012
Mugil platanus	Mp	S/SE/NE	74	4	Same	Begossi and others 2008, Kütter and others 2009, Nunes and others 2011, Bisi and others 2012
Mycteroperca acutirostris	Mac	SE/NE	67	None	None	Begossi and others 2008, Begossi and others 2012a
Mycteroperca bonaci	Mb	SE/NE	78	None	None	Begossi and others 2008, Begossi and others 2012a
Oligoplites saliens	Os	S/SE	47	None	None	Begossi and others 2008, Nunes and others 2011

Table 1. continued

Fish species	Codes[1]	Region[2]	N fishers[3]	N fish Hg[4]	Species Hg	Sources
Pomatomus saltatrix	Ps	S/SE/NE	162	227	Same	Begossi and others 2008, Kütter and others 2009, Silvano and Begossi 2005, 2010, Nunes and others 2011
Scomberomorus brasiliensis	Sb	SE/NE	46	None	None	Begossi and others 2008
Seriola lalandi	Sl	SE/NE	46	None	None	Begossi and others 2008
Seriola spp.	Se	SE	28	44	*S. dumerili*	Cai and others 2007, Silvano and Begossi 2012
Stegastes fuscus	Sf	SE	21	None	None	Begossi and others 2008
Trichiurus lepturus	Tl	SE	21	120	Same	Begossi and others 2008, Barbosa and others 2011, Bisi and others 2012
Umbrina coroides	Uc	SE	21	6	*U. canosai*	Begossi and others 2008, Bisi and others 2012

Fish species analyzed in the Brazilian coast, showing the number of fishers interviewed (n = 478 total fishers in 20 sites) to estimate trophic levels and the number of fish analyzed for mercury (Hg) content for the same or similar (same genus) fish species. Literature sources either for fishers' knowledge or for mercury content are in the references
[1]*Codes refer to fish species codes in Figures 1A, 2A, and 3A.*
[2]*Regions are south (S), southeastern (SE), and northeastern (NE) coasts, where interviews were conducted with fishers.*
[3]*Number of fishers (N fishers) interviewed about each fish species (some fish species were addressed in the same study, involving the same fishers).*
[4]*Number of fish (N fish Hg) analyzed for mercury content, indicating if the same or similar species were analyzed in ecotoxicology studies.*
[5]*'None' means that neither did we find data on mercury content of that fish species, nor of similar species from the same genus.*

fish that are sheltered in the flooded forest) (Silva and Begossi 2009; Hallwass and others 2011). The main fish species caught are the tucunarés (*Cichla* spp., Cichlidae) in Negro River (Begossi and others 2008; Silvano and others 2008; Silva and Begossi 2009) and the curimata (*Prochilodus nigricans*), pescada (*Plagioscion squamosissimus*), and mapara (*Hypophthalmus marginatus*) in the Tocantins River (Hallwass and others 2011). More information about the studied sites and people is provided in the original surveys (Table 1).

In all surveys, we interviewed fishers following the same standardized methodology: individual interviews were performed according to structured questionnaires, showing fish species using photographs. We selected the interviewed fishers through snow-ball sampling: after locating some fishers with the help of local contacts (usually community leaders), we asked the interviewed fishers to indicate others. Other fishers were then interviewed if they fulfilled certain criteria, such as being a full-time fisher, having lived in the region for at least 10 years, and having at least 15 years of fishing expertise. More details about the interview methodology are provided in the original surveys (Begossi and others 2008, 2011; Silvano and others 2008; Silvano and Begossi 2012; Hallwass and others 2013). Here, we analyzed only the fishers' answers to the question 'What does this fish eat?,' which were included in all surveys.

Fish Trophic Levels

To estimate fish TLs from fishers' knowledge, we first calculated the percentage of interviewed fishers in each study who mentioned each food item for each studied fish. We grouped the food items into major categories and a TL was assigned for each category consumed by fish. For coastal fish, the food categories and corresponding fish TLs were as follows: algae (TL = 2), herbivorous (other vegetal matter and plankton, TL = 2), detritus (TL = 2), shrimp (TL = 3), crab (TL = 3), mollusk (usually squid and octopus, TL = 4), and fish (TL = 4). For freshwater fish, the food categories and corresponding fish TLs were as follows: fruits and seeds (TL = 2), other plants and flowers (aquatic plants, leaves, and other parts of terrestrial plants, TL = 2), detritus (including mud and algae, TL = 2), terrestrial invertebrates (insects, spiders, earthworms, TL = 3), aquatic invertebrates (crustaceous, usually shrimp, TL = 3), and terrestrial vertebrates (birds, frogs, and others, TL = 4), and fish (TL = 4). These values of TL for each category were assigned based on previous studies and on the

Table 2. Data from Fish Species Analyzed in the Brazilian Amazon (Freshwater)

Fish species	Codes[1]	Region[2]	N fishers[3]	N fish Hg[4]	Species Hg	Sources
Arapaima gigas	Ag	Tocantins	137	6	Same	Unp.[6], Bastos and others 2008
Auchenipterichthys longimanus	Al	Negro	29	None[5]	None	Silvano and others 2008, Begossi and others 2008
Brachyplatystoma filamentosum	Bfi	all	166	20	Same	Unp., Bastos and others 2008, Begossi and others 2008, Beltran-Pedreros and others 2011
Brycon cephalus[7]	Bc	Negro	29	14	Same	Bidone and others 1997, Begossi and others 2004, Silvano and others 2008, Bastos and others 2008, Begossi and others 2008, Beltran-Pedreros and others 2011
Brycon falcatus	Bfa	Tocantins	137	32	*Brycon* spp.	Unp., Bidone and others 1997, Begossi and others 2004, Bastos and others 2008
Brycon melanopterus	Bm	Negro	29	22	Same	Silvano and others 2008, Bastos and others 2008, Begossi and others 2008, Beltran-Pedreros and others 2011
Cichla kelberi	Ck	Tocantins	137	78	*Cichla* spp.	Unp., Kehrig and others 2009
Cichla monoculus	Cm	Negro	29	113	*Cichla* spp.	Silvano and others 2008, Bastos and others 2008, Begossi and others 2008, Beltran-Pedreros and others 2011
Cichla temensis	Ct	Negro	29	4	Same	Silvano and others 2008, Bastos and others 2008, Begossi and others 2008
Geophagus proximus	Gp	Tocantins	137	124	*Geophagus* spp.	Unp., Bastos and others 2008, Kehrig and others 2009
Hoplarchus psittacus	Hp	Negro	29	None	None	Begossi and others 2008
Hoplias malabaricus	Hm	Tocantins	137	152	Same	Unp., Mol and others 2001, Belger and Forsberg 2006, Bastos and others 2008, Silva and others 2012
Hypophthalmus marginatus	Hym	Tocantins	137	11	Same	Unp., Beltran-Pedreros and others 2011
Leporinus affinis	La	Tocantins	137	None	None	Unp.
Leporinus agassizii	Lag	Negro	29	None	None	Silvano and others 2008, Begossi and others 2008
Leporinus falcipinnis	Lf	Negro	29	None	None	Silvano and others 2008, Begossi and others 2008
Leporinus fasciatus	Lfs	Negro	29	7	Same	Silvano and others 2008, Bastos and others 2008, Begossi and others 2008
Metynnis hypsauchen	Mh	Negro	29	None	None	Silvano and others 2008, Begossi and others 2008
Myleus rubripinnis	Mr	Negro	29	50	*Myleus* spp.	Bidone and others 1997, Begossi and others 2004, Silvano and others 2008, Begossi and others 2008
Myleus torquatus	Mt	Negro	29	50	*Myleus* spp.	Bidone and others 1997, Begossi and others 2004, Silvano and others 2008, Begossi and others 2008
Mylossoma duriventre	Md	Tocantins	137	21	Same	Unp., Bastos and others 2008, Beltran-Pedreros and others 2011
Osteoglossum bicirrhosum	Ob	Negro	29	13	Same	Bastos and others 2008, Begossi and others 2008, Beltran-Pedreros and others 2011
Piaractus brachipomus	Pb	Tocantins	137	12	Same	Unp., Bastos and others 2008, Beltran-Pedreros and others 2011
Pimelodus albofasciatus	Pa	Negro	29	17	Same	Bastos and others 2008, Begossi and others 2008
Pinirampus pirinampu	Pp	Negro	29	44	Same	Bastos and others 2008, Begossi and others 2008, Beltran-Pedreros and others 2011
Plagioscion squamosissimus	Ps	Tocantins	137	117	Same	Unp., Mol and others 2001, Bastos and others 2008, Beltran-Pedreros and others 2011
Prochilodus nigricans	Pn	Negro	29	10	Same	Begossi and others 2004, Beltran-Pedreros and others 2011

Table 2. continued

Fish species	Codes[1]	Region[2]	N fishers[3]	N fish Hg[4]	Species Hg	Sources
Pseudoplatystoma fasciatum	Pf	Tocantins	137	50	Same	Bidone and others 1997, Begossi and others 2004, Bastos and others 2008, Begossi and others 2008
Pygocentrus nattereri	Pn	Negro	29	25	Same	Begossi and others 2004, Bastos and others 2008
Semaprochilodus brama	Sb	Tocantins	137	34	Same	Unp., Bidone and others 1997, Begossi and others 2004
Semaprochilodus insignis	Si	Tocantins	137	13	Same	Begossi and others 2008, Beltran-Pedreros and others 2011
Semaprochilodus taeniurus	St	Negro	29	9	Same	Begossi and others 2008, Beltran-Pedreros and others 2011
Serrasalmus gouldingi	Sg	Negro	29	None	None	Silvano and others 2008, Begossi and others 2008
Serrasalmus rhombeus	Sr	Negro	29	234	Same	Mol and others 2001, Silvano and others 2008, Bastos and others 2008, Begossi and others 2008
Serrasalmus serrulatus	Ss	Negro	29	None	None	Silvano and others 2008, Begossi and others 2008
Uaru amphiacanthoides	Ua	Negro	29	None	None	Begossi and others 2008

Fish species analyzed in the Brazilian Amazon (freshwater), showing the number of fishers interviewed (n = 166 total fishers in two rivers) to estimate trophic levels and the number of fish analyzed for mercury (Hg) content for the same or similar (same genus) fish species. Literature sources either for fishers' knowledge or for mercury content are in the references.

[1]*Codes refer to fish species codes in Figures 1B, 2B, and 3B.*

[2]*Regions are Negro or Tocantins Rivers (or both).*

[3]*Number of fishers (N fishers) interviewed about each fish species (some fish species were addressed in the same study, involving the same fishers).*

[4]*Number of fish (N fish Hg) analyzed for mercury content, indicating if the same or similar species were analyzed in ecotoxicology studies.*

[5]*'None' means that neither did we find data on mercury content of that fish species, nor of similar species from the same genus.*

[6]*Fishers' knowledge on diet of fish from the Tocantins River are from unpublished data (Unp.) of R.A.M.S. and A.B.*

[7]*The name of Brycon cephalus has changed to Brycon amazonicus.*

FishBase website (Froese and Pauly 2015). We could not establish the same food categories for coastal and freshwater ecosystems, due to ecological differences between fish communities. The nomenclature provided by the fishers when describing fish diets was usually not sufficiently detailed to allow taxonomic identification of food items beyond the family level, except for certain fish. However, we did not discriminate among the fish species reported by fishers in the diet of piscivorous fish, which were assigned the same TL, irrespective of the species of fish consumed. If the same fish species were addressed in more than one site or study (Tables 1 and 2), we averaged the percentages of fishers who mentioned each food item and calculated the TL based on this averaged value. After calculating the percentage of fishers who mentioned each food item and its corresponding TL, we calculated the overall TL for each fish according to the fishers in two steps. First, we multiplied the TL of each food item by the percent of fishers who cited that food item, and then we summed these products across all food items. Second, this sum was then divided by the sum of the percentages of fishers who cited each food item across all food items. For example, fishers from the Negro River mentioned that the tucunaré (*Cichla temensis*) eats fish (TL = 4, 62.1% of fishers) and aquatic invertebrates (TL = 3, 13.8%, the sum is less than 100% because some fishers did not know what this fish eats). Therefore, the TL of this fish, according to fishers, was estimated as follows: $(4 \times 62.1) + (3 \times 13.8) = 289.7$, then $289.7/75.9 = 3.8$.

We obtained the TLs of the studied fish species from the literature through the FishBase website (Froese and Pauly 2015), as this compilation is regularly used in biological studies and is a useful source to get standardized values of TL for all studied fishes. The values of TL reported for fish species in FishBase came from two main sources: (1) TL based on diet composition studies, and (2) TL based on reported food items. Diet composition studies are published studies that describe in some detail the diet composition of fish species through examination and quantification of stomach contents and the resulting volumetric composition of food items consumed. The main references from these diet studies for the studied fishes according to FishBase are listed in Tables 3 and 4. For some fish species, published studies on diet composition are lacking, but food items have been reported. For such cases, TL was estimated based on a randomized resampling routine for the known food items, as explained on the FishBase website (Froese and Pauly 2015). In addition, some of the lesser studied fish species had their TL estimated based on size and trophic position of their closest relatives (Froese and Pauly 2015). For some fish species, TL was estimated by both the diet composition method and the reported food item method (Tables 3 and 4). In such cases, we averaged the two estimates to obtain a unique measure of TL based on the literature for those fish species.

Fish Mercury Content

We gathered data on the total mercury (Hg) content (wet weight) in fish muscle from the literature for a subset of the studied fish species (15 coastal and 26 freshwater species) (Tables 1 and 2). We standardized all measures of mercury content as units of μg/g of wet tissue for analysis. Although we aimed to obtain data on the Hg contents of the same fish species in the same regions (Brazilian coast and Amazon Basin) for which we had data on TLs, we sometimes included data for the same species in other regions, or for other species of the same genus (Tables 1 and 2). Substitution of another species of the same genus occurred more frequently for Brazilian coastal fish than for Brazilian Amazon fish (Tables 1 and 2). The number of Hg content samples for some of the coastal species was based on less than five fish (Table 1).

Analyses

To compare TL based on the literature with TL based on fishers' knowledge, we first performed a correlation analysis for both coastal species and freshwater species, considering fish species as the sampling unit. For both the coastal species and the freshwater species, we calculated the Pearson coefficient of correlation between TL based on the literature and TL based on fishers' knowledge, and we also determined whether this correlation coefficient was significantly different from zero. We opted for the correlation analysis because it does not imply any causal relation between the two sources of knowledge being compared (TL based on the literature with TL based on fishers' knowledge). In addition, we performed a t-test for paired comparisons for both coastal species and freshwater species to determine whether TL based on the literature was significantly different from TL based on fishers' knowledge.

We performed linear regression analyses considering fish TL (based on information from either fishers or the literature, one analysis for each) as the independent variable and the Hg content of fish as the dependent variable, with the fish species as

Table 3. Trophic Levels and Maximum Length for Fish Species Analyzed in the Brazilian Coast

Fish species	Codes[1]	TL food items[2]	TL diet studies[3]	TL closest relatives[4]	Maximum length (cm)	Main source TL diet
Abudefduf saxatilis	As	2.8	3.8		22.9	Randall 1967
Bodianus pulchellus	Bp	3.6	NA		28.5	Baensch and Debelius 1997
Bodianus rufus	Br	3.4	3.7		40	Randall 1967
Caranx crysos	Cc	3.6	4.1		70	Randall 1967
Caranx latus	Cl	3.9	4.2		101	Randall 1967
Centropomus parallelus	Cp	4.2	NA		72	Boujard and others 1997
Cephalopholis fulva	Cf	4.3	4.1		41	Randall 1967
Cynoscion jamaicensis	Cj	3.8	4.2		50	Gómez-Canchong and others 2004
Epinephelus itajara	Ei	4	4.1		250	Randall 1967
Epinephelus marginatus	Ema	4.1	4.4		150	Derbal and Kara 1996
Epinephelus morio	Emo	3.6	3.5		125	Gómez-Canchong and others 2004
Epinephelus niveatus	En	4	NA		122	Heemstra and Randall 1993
Eucinostomus argenteus	Ea	3.3	3.2		20	Austin and Austin 1971
Euthynnus alleteratus	Eal	4	4.5		122	Bowmanand others 2000
Haemulon aurolineatum	Ha	3.2	4.4		25	Randall 1967
Hemiramphus balao	Hb	3.7	3.9		40	Randall 1967
Hippocampus reidi	Hr	NA	NA	3.4	17.5	NA
Kyphosus spp.[5]	Ks	2.3	2		166	Randall 1967
Lutjanus synagris	Ls	3.7	3.8		60	Rodríguez Pino 1962
Menticirrhus americanus	Ma	NA	3.5		50	Bowman and others 2000
Micropogonias furnieri	Mf	3.3	3.1		60	Sierra and others 1994
Mugil curema	Mc	2.4	2		90	Gómez-Canchong and others 2004
Mugil platanus	Mp	2	NA		80	NA
Mycteroperca acutirostris	Mac	3.4	NA		80	NA
Mycteroperca bonaci	Mb	4.5	4.3		150	Randall 1967
Oligoplites saliens	Os	3.8	NA		50	NA
Pomatomus saltatrix	Ps	4.1	4.5		130	Bowman and others 2000
Scomberomorus brasiliensis	Sb	4.4	3.3		125	Gómez-Canchong and others 2004
Seriola lalandi	Sl	3.9	4.2		250	Craig 1960
Seriola spp.[6]	Se	4.3	4.5		175	Bowman and others 2000 Barreiros and others 2003
Stegastes fuscus	Sf	3.3	NA		12.6	NA
Trichiurus lepturus	Tl	4.2	4.4		234	Portsev 1980
Umbrina coroides	Uc	3.3	3.1		35	Gómez-Canchong and others 2004

Trophic levels and maximum length (total length in cm for male fish) estimated through two methods in the Fishbase website (Froese and Pauly 2015) for fish species analyzed in the Brazilian coast with main references for fish diet. NA = information nonavailable.
[1]*Codes refer to fish species codes in Figures 1A, 2A, and 3A.*
[2]*Trophic level is estimated from a number of food items using a randomized resampling routine (Froese and Pauly 2015)*
[3]*Trophic level calculated from diet tables from published studies of the diet of the fish species through stomach content analyses and the resulting volumetric composition of food items. Main reference to the diet table is provided in the last column.*
[4]*Trophic level estimated based on size and trophic position of closest relatives (Froese and Pauly 2015).*
[5]*We searched data for the species Kyphosus incisor and K. sectatrix and averaged values of TL reported in Fishbase (Froese and Pauly 2015).*
[6]*We searched data for the species Seriola dumerili and S. rivoliana and averaged values of TL reported in Fishbase (Froese and Pauly 2015).*

sampling units. We chose regression analysis because there is a known causal relationship between these two variables: a higher TL would potentially increase the Hg content of a given fish species through the bioaccumulation process (Bisi and others 2012).

Table 4. Trophic Levels and Maximum Length for Fish Species Analyzed in the Brazilian Amazon (Freshwater)

Fish species	Codes[1]	TL food items[2]	TL diet studies[3]	TL closest relatives[4]	Maximum length (cm)	Main source TL diet
Arapaima gigas	Ag	4.5	4.5		450	Soares and others 1986
Auchenipterichthys longimanus	Al	NA	NA	3.4	15	NA
Brachyplatystoma filamentosum	Bfi	4.5	NA		360	NA
Brycon cephalus	Bc	2	NA		45	NA
Brycon falcatus	Bfa	NA	NA	2.6	37	NA
Brycon melanopterus	Bm	2.5	NA		30	NA
Cichla kelberi	Ck	NA	NA	4.1	27.6	NA
Cichla monoculus	Cm	3.9	NA		70	NA
Cichla temensis	Ct	4.5	4.5		99	Williams and others 1998
Geophagus proximus	Gp	NA	NA	2.2	22.5	NA
Hoplarchus psittacus	Hp	3.7	NA		32	NA
Hoplias malabaricus	Hm	3.8	4.5		55.2	Soares and others 1986
Hypophthalmus marginatus	Hym	3.4	NA		55	NA
Leporinus affinis	La	2.3	NA		25	NA
Leporinus agassizii	Lag	NA	NA	2.2	23.4	NA
Leporinus falcipinnis	Lf	NA	NA	2.2	NA	NA
Leporinus fasciatus	Lfs	3	NA		30	NA
Metynnis hypsauchen	Mh	NA	NA	2.9	15	NA
Myleus rubripinnis	Mr	2	NA		39	NA
Myleus torquatus	Mt	NA	NA		NA	NA
Mylossoma duriventre	Md	2.8	NA		25	NA
Osteoglossum bicirrhosum	Ob	3.4	NA		90	NA
Piaractus brachipomus	Pb	2.5	NA		88	NA
Pimelodus albofasciatus	Pa	NA	NA	3.3	25	NA
Pinirampus pirinampu	Pp	4.5	NA		120	NA
Plagioscion squamosissimus	Ps	4	4.4		80	Williams and others 1998
Prochilodus nigricans	Pn	2.4	NA		37	NA
Pseudoplatystoma fasciatum	Pf	4.4	NA		104	NA
Pygocentrus nattereri	Pn	3.7	NA		50	NA
Semaprochilodus brama	Sb	NA	NA		28	NA
Semaprochilodus insignis	Si	2	NA		27	NA
Semaprochilodus taeniurus	St	2	NA		24	NA
Serrasalmus gouldingi	Sg	NA	NA	3.6	27.9	NA
Serrasalmus rhombeus	Sr	3.6	4		41.5	Goulding 1980
Serrasalmus serrulatus	Ss	NA	NA	3.5	19	NA
Uaru amphiacanthoides	Ua	2.8	NA		25	NA

Trophic levels and maximum length (total length in cm for male fish) estimated through two methods in the Fishbase website (Froese and Pauly 2015) for freshwater fish species analyzed in the Brazilian Amazon with main references for fish diet. NA = information nonavailable.
[1]*Codes refer to fish species codes in Figures 1B, 2B, and 3B.*
[2]*Trophic level is estimated from a number of food items using a randomized resampling routine (Froese and Pauly 2015).*
[3]*Trophic level calculated from diet tables from published studies of the diet of the fish species through stomach content analyses and the resulting volumetric composition of food items. Main reference to the diet table is provided in the last column.*
[4]*Trophic level estimated based on size and trophic position of closest relatives (Froese and Pauly 2015).*

Results and Discussion

Comparison of TL Based on the Literature with TL Based on Fishers' Knowledge

The fish TLs estimated from fishers' knowledge were positively correlated with the fish TLs estimated from the biological literature for both coastal ($r = 0.8$, $n = 33$; $P < 0.001$) (Figure 1A) and freshwater fish ($r = 0.72$, $n = 36$; $P < 0.001$) (Figure 1B). Nevertheless, the average values of TL were higher for the biological literature (3.67 ± 0.62 SD) compared with fishers' knowl-

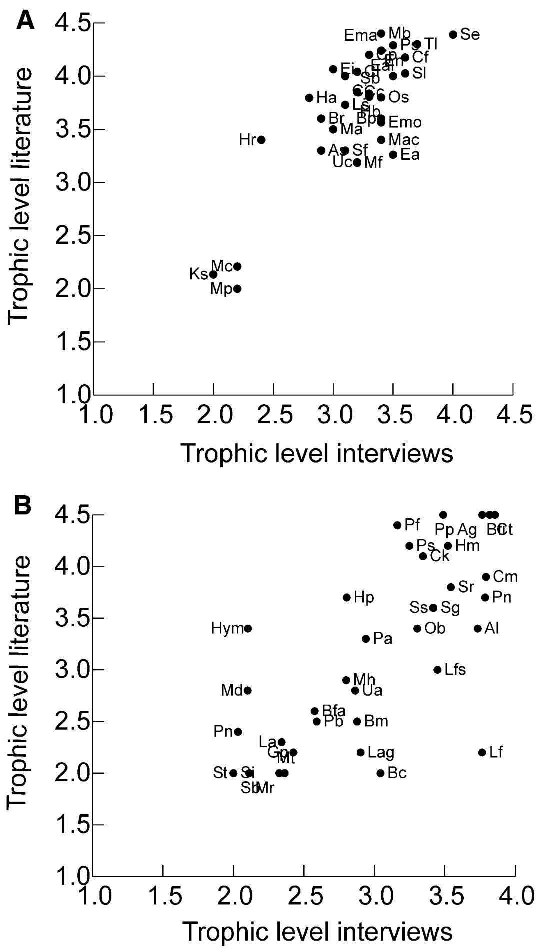

Figure 1. Trophic levels of fish species based on fishers' knowledge and the literature. Correlation between the trophic levels of fish species estimated from fishers' interviews and the biological literature for **A** coastal fish species ($r = 0.8$, $n = 33$; $P < 0.001$) and **B** freshwater fish species of the Amazon Basin ($r = 0.72$, $n = 36$; $P < 0.001$). The *codes* correspond to the first letter of the fish genus and species. The names of coastal and freshwater fish are provided in Tables 1 and 2, respectively.

edge (3.17 ± 0.44) for coastal fishes ($t = -7.5$, df = 32, $P < 0.001$). Overall, the TL estimated from fishers' knowledge were lower than that estimated from the literature for most coastal fish species (Figure 2A). A plausible explanation for this difference would be that the TL estimate based on the literature was more refined than that based on fishers' knowledge, in that the trophic level of each fish appearing in the diet was taken into account when calculating TL based on the literature. Such a distinction was not made in calculating TL based on fishers' knowledge. In this sense, a fish that eats omnivorous fish would have a higher TL than a fish-eating herbivorous fish. Nevertheless, this limitation could be easily addressed in future studies by asking fishers to provide more details about the fish species consumed by a particular fish, as fishers usually accurately recognize the diet of piscivorous fish (Begossi and Silvano 2008; Silvano and Begossi 2005, 2010). Although TL based on the literature was significantly higher than TL based on fishers' knowledge for coastal fish species, the two estimates of TL were positively and significantly related. Thus, TL based on fishers' knowledge should still be a useful index of the TL of coastal fish.

The average values of TL did not significantly differ between the biological literature (3.2 ± 0.92) and fishers' knowledge (3 ± 0.62) for freshwater fishes ($t = -1.48$, df = 35, $P = 0.15$) (Figure 2B). Thus, for freshwater fish species, there was a good agreement between the TL estimate based on the literature and the TL estimate based on fishers' knowledge. Again, we concluded that TL based on fishers' knowledge should serve as a useful index of the TL of freshwater fish. The comparison that we made here considered both sources of knowledge as being equally valid and reliable (Silvano and Valbo-Jorgensen 2008), not assuming a priori that knowledge from formal scientific studies would be more important than fishers' knowledge. The results from correlation analyses indicated that these two sources of knowledge on fish TL (fishers' knowledge and biological literature) showed the same trend of variation. This trend may reflects the 'true' value of fish TL, which is related to what fish actually eat in the wild and is similarly estimated by either the biological literature or fishers' knowledge.

Moving Beyond: Can Fishers' Knowledge Indicate Bioaccumulation?

We also observed a positive relationship between the fish Hg contents estimated from the literature and fish TLs estimated from fishers' knowledge for both coastal ($r^2 = 0.32$, $F_{1,13} = 6.01$; $P = 0.03$) (Figure 3A) and freshwater fish ($r^2 = 0.53$, $F_{1,24} = 26.9$; $P < 0.001$) (Figure 3B). The relationship between TL based on fishers' knowledge and Hg contents was weaker for coastal fishes than for freshwater fishes (Figure 3). The fish TLs estimated from the literature were also positively and significantly related to Hg contents for freshwater fish ($r^2 = 0.67$, $F_{1,24} = 48.3$; $P < 0.001$). Interestingly, the fish TLs estimated from the literature were unrelated to the Hg content of coastal fish ($r^2 = 0.2$, $F_{1,13} = 3.9$; $P = 0.07$). Perhaps the weaker relationship between TL based on fishers' knowledge

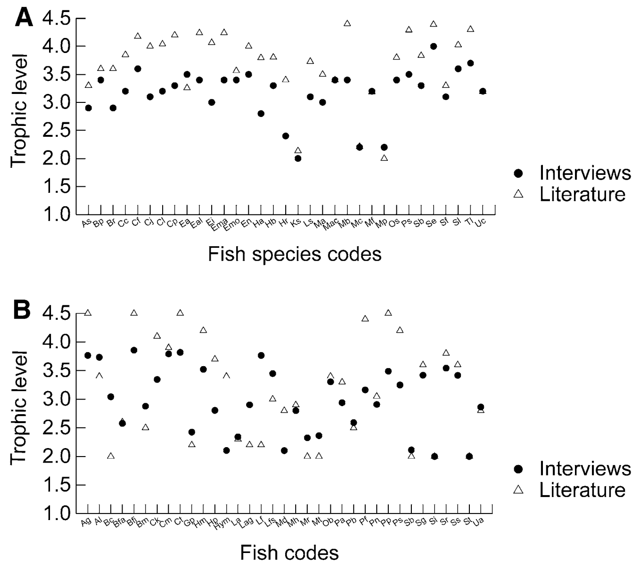

Figure 2. Paired comparison of trophic levels of fish species based on fishers' knowledge and the literature. Values of trophic levels of fish species estimated from fishers' interviews and the biological literature for **A** coastal fish species ($t = -7.5$, df = 32, $P < 0.001$) and **B** freshwater fish species of the Amazon Basin ($t = -1.48$, df = 35, $P = 0.15$). The *codes* correspond to the first letter of the fish genus and species. The names of coastal and freshwater fish are provided in Tables 1 and 2, respectively.

and Hg contents for coastal fishes compared with freshwater fishes was attributable to inaccurate estimation of Hg content for some of the coastal fishes stemming from small sample size. For some of the coastal fishes, estimation of the mean Hg content was based on fewer than five samples (Table 1).

In Brazil, mercury pollution may be caused mainly by industrial and domestic effluents, in addition to atmospheric emissions in the coast (Kütter and others 2009) and also by gold mining in the rivers of the Amazon Basin (Boischio and Henshel 2000; Bastos and others 2008). We showed that fishers' knowledge adequately reflected the bioaccumulation process that is usually reported in biological studies conducted in coastal and freshwater ecosystems (Boischio and Henshel 2000; Bisi and others 2012), as fish of higher TLs (usually piscivorous) (Figure 1A, B) show higher contents of Hg (Figure 3A, B). Interestingly, this knowledge may be linked to fishers' behavior, as fish trophic levels may influence the cultural choices of Brazilian fishers regarding the fish species that are preferred or avoided as taboo foods (Begossi and others 2004). Therefore, fishers' knowledge about fish diets could be applied to rapidly estimate fish TLs and, hence, to estimate fish Hg contents. For example, the fish *Hoplarchus psittacus* exhibits a TL of 2.8, and we could not find any studies reporting the Hg content of this fish. According to our results, this fish would present an estimated Hg content of 0.25 µg/g of muscle wet weight, with upper and lower limits of 0.57 and 0.08, respectively (considering the regression equation shown in Figure 3B and the standard error of the coefficient). A precautionary approach would be to consider the upper limit, and further studies could assess precise contamination values.

Limitations and Future Directions

Although our results are limited to a single country, we considered Brazil to be a promising and suitable study case for investigating potential applications of fishers' knowledge to improve the scientific understanding of fish trophic ecology for a number of reasons. First, fishing is an important economic activity that involves thousands of fishers, either along coastlines or in large rivers and reservoirs. Second, a large proportion of the fish caught come from small-scale fishers, who catch hundreds of fish species in diverse tropical and subtropical marine, estuarine and freshwater ecosystems. Indeed, some of the studied fish species have widespread or even global distributions, such as the bluefish (*Pomatomus saltatrix*) (Silvano and Begossi 2005, 2010) and the dusky grouper (*Epinephelus marginatus*) (Begossi and Silvano 2008), which may increase the scope of our results. Third, formal scientific studies are still scarce for many fish spe-

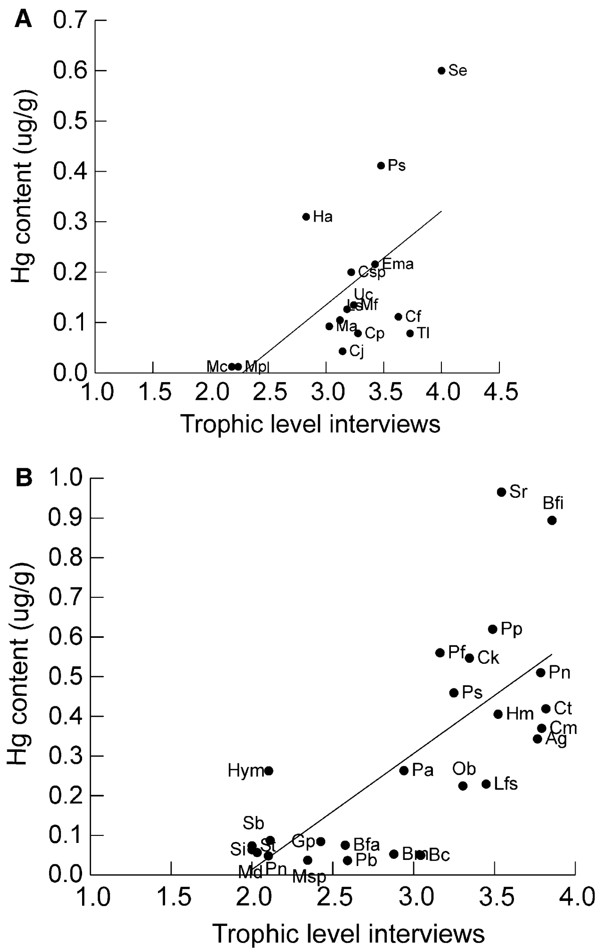

Figure 3. Trophic levels of fish species based on fishers' knowledge and fish contamination. Regression between the fish trophic levels (TLs) estimated from fishers' knowledge (independent variable) and the total mercury (Hg) contents (μg/g of fish muscle wet weight, dependent variable) of **A** coastal fish species ($n = 15$), ($r^2 = 0.32$; $P = 0.03$) (the regression equation was fish Hg content = −0.42 (±0.24) + 0.186 (±0.075) × fish TL); and **B** freshwater fish species ($n = 26$) ($r^2 = 0.53$; $P < 0.001$) (the regression equation was fish Hg content = −0.57 (±0.17) + 0.292 (±0.056) × fish TL). The *codes* correspond to the first letter of the fish genus and species. The names of coastal and freshwater fish are presented in Tables 1 and 2, respectively.

cies in several Brazilian regions, and the government has a limited capacity to conduct these studies or to enforce management recommendations (Begossi 2010). For example, it is noteworthy that the scarcity of formal scientific studies about freshwater fish species in the Brazilian Amazon (Table 4) compared to the better known coastal fishes (Table 3) that have a more widespread distribution, occurring also in other countries (Silvano and Begossi 2005; Froese and Pauly 2015). The Fishbase website (Froese and Pauly 2015) brings references for diet studies of only 5 of 36 studied fish species in the Brazilian Amazon; 10 fish species had their trophic levels estimated based on closest relatives because of lack of data on diet or food items, and even maximum length was unknown for two species (Table 4). In such a data-poor scenario (Johannes 1998), the detailed knowledge of local fishers (Begossi and others 2008; Silvano and others 2008) would be of value in making decisions regarding fisheries management and contamination potential. Fourth, several studies have shown that Brazilian fishers have well-developed knowledge about fish diets (Silvano and others 2008; Silvano and Begossi 2005, 2012; Ramires and others 2015), and the local knowledge of fishers about fish diet agrees with comparative data from biological surveys (Begossi and Silvano 2008; Silvano and Begossi 2010). Fishers possibly obtain such detailed knowledge in fish diets either from direct observations while gutting fish or by using baits (Silvano and Begossi 2002, 2005). For example, fishers in the Negro River, in the Brazilian Amazon, recognize several seeds as potential baits to catch frugivorous fishes (Silvano and others 2008). This kind of knowledge on fish diets is far more developed than knowledge about other biological aspects, such as reproduction (Silvano and Begossi 2002) and is usually widespread among fishers of all age classes.

We recognize that fish TLs estimated from fishers' knowledge are only a proxy for Hg contents and are not a substitute for consistent biological surveys, as the Hg content of fish may vary according to the season, fish size, and other environmental factors (Bastos and others 2008; Bisi and others 2012). Fishers' knowledge is a complement to biological knowledge, and the former type of information could and should be cross-checked and compared with data from either biological or fisheries surveys (Begossi and Silvano 2008; Aswani and Hamilton 2004; Silvano and Begossi 2010; Hallwass and others 2013). Moreover, we recognize that our survey has some limitations. The fish addressed in interviews and analyzed to determine that Hg contents came from several distinct regions. Additionally, the sampling sizes determined from the interviewed fishers or in the analyses of fish varied and were sometimes small (less than 10 individuals), and some of the Hg data came from another species of the same genus (Tables 1 and 2). Nevertheless, the fact that we observed a significant and positive relationship between fish TLs and Hg contents even considering these limitations of the dataset is encouraging and indicates the potential of fishers' knowledge to indicate bioaccumulation in fish. Future studies could match fishers' knowledge of fish diets with fish Hg contents for the same species in the same region, to improve the accuracy of the estimation of fish contamination. However, even the approximate estimates of the contamination potential provided by fishers' knowledge could be useful for devising public health strategies, evaluating environmental impacts and indicating the need for more detailed surveys. Furthermore, fishers' knowledge may be useful for estimating the contamination potential of other aquatic organisms, as fishers are also aware of the diets of top aquatic predators, such as dolphins and sharks (Manzan and Lopes 2015; Ramires and others 2015). These large aquatic animals are fish predators, exhibiting higher trophic levels and potentially accumulating pollutants (Dorneles and others 2010). Data on fish diets obtained from local fishers have also been used to develop qualitative models of aquatic food webs along the coast of Africa (Le Fur and others 2011) and to assess the indirect impacts of fishing through depletion of fish prey in the tropical Pacific (Johannes and others 2000). Therefore, fishers' knowledge on fish diets could be applied worldwide, especially in regions where there are small-scale fishers and biological data may be lacking. Moreover, several data-poor countries suffer from organic waste and industrial pollutants, which makes fisher's knowledge even more critical in these regions.

Conclusions

This is possibly the most comprehensive analysis of fishers' knowledge on fish diets and, to our knowledge, the first study to show a potential application of fishers' knowledge to improve research on ecotoxicology in marine and freshwater ecosystems. In addition to improving the existing knowledge base on fish trophic interactions, fishing impacts on aquatic food webs, and fish contamination and human health, this new application of fishers' knowledge may stimulate much-needed cooperation between biologists and fishers. This cooperation may ultimately strengthen the cultural and political status of artisanal fishers.

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